ALL-SILICON ENERGY STORAGE (ASES)

A. Datas, A. Martí, C. del Cañizo and A. Luque
Instituto de Energía Solar – Universidad Politécnica de Madrid (IES-UPM), Spain
Avda. Complutense, 30 (Madrid, Spain)

ABSTRACT: Silicon is an ideal candidate to build massive energy storage solutions owing to its low cost (~$1.7/kg) and abundance on earth. In this work, we describe a novel concept for energy storage in which the energy is stored in the form of silicon's latent heat and converted to electricity upon demand by thermophotovoltaic (TPV) cells. This approach takes advantage of the extremely high latent heat (1.8 MJ/kg) and melting point (1410ºC) of silicon, and the low weight and silent operation of the TPV cells. The proposed solution has potential to provide total energy (heat plus electricity) storage densities approaching 1 MWh/m^3, which is 12-15 times higher than that of lead-acid batteries, 2-5 times than that of Li-ion batteries and 10-20 times than that of the molten salt PCMs utilized in CSP systems. In the proposed system, 10-50% of the total energy could be delivered in the form of electricity, depending on the particular TPV cell characteristics, and the remaining energy is supplied as heat (e.g. hot water) which could be used in homes or factories.
Keywords: thermophotovoltaics, storage, thermal energy storage, silicon, phase change material.

1 INTRODUCTION

Developing novel energy storage (ES) technologies at competitive cost and utilizing abundant materials is essential in order to manage a future electric system based on renewables. Today's global ES capacity is less than 3% of the installed power capacity and 95% of this capacity is provided by pumped hydroelectric systems [1], which is restricted to locations with very particular characteristics. The global demand of advanced ES systems (both heat and electricity) is expected to grow to 32,000 TWh by 2035, a 70% increase from 2012. Specifically, more than 6,000 GW of new global electricity storage capacity is expected to be required by 2030 [2].

Nowadays, there is no definitive ES solution. In the field of electricity storage, some of the existing technologies (e.g. batteries) are affected by scarcity and supply risk of relevant materials such as lithium, cobalt, tantalum or rare earths [1]. Some others must solve serious security issues (e.g. hydrogen and NaS batteries). In the field of thermal energy storage (TES) for power generation the existing technologies (most of them based on molten salts) are either inefficient or have a high cost [3].

In this paper we will analyze a novel TES concept that has the potential to achieve one of the highest energy densities among the existing ES solutions and uses silicon, an abundant, cheap and safe material. In this system, energy is stored as latent heat in the phase change of silicon and the energy is released in the form of electricity by means of thermophotovoltaic (TPV) cells (Fig.1). The energy not converted into electricity by the TPV cells is delivered in the form of heat (e.g. hot water).

The two key differentiating features of this system are: (1) the use of high melting point (1410 ºC) and high latent heat (1.8 MJ/kg) silicon phase-change material (PCM) for thermal energy storage (TES), and (2) the use of TPV cells, instead of conventional heat engines, for power production. The latter allows extremely high storage temperature, well above silicon's melting point, due to the absence of physical contact between the heat source (the molten silicon) and the power engine (the TPV cell). Other benefits of utilizing TPV cells are: (i) extremely high power densities (power-to-weight and power-to-volume ratio), (ii) low maintenance costs (neither moving parts nor working fluids within the converter), and (iii) silent operation, which is important for decentralized ES applications (in towns).

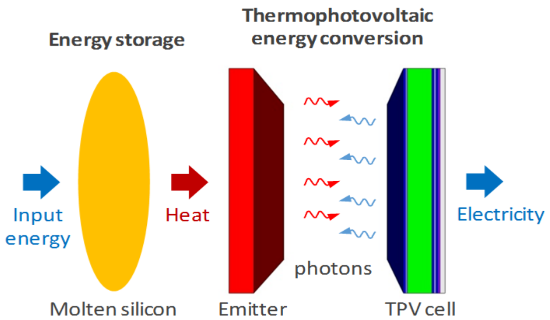

Fig. 1. High temperature thermal energy storage in molten silicon and TPV energy conversion.

2 SYSTEM DESCRIPTION

2.1 Overall design

Fig.2 shows two possible configurations of the TES system [4]: electric and solar. In the first case a highly electrically conductive solenoid surrounds the vessel containing the silicon. When alternating current passes through the solenoid, the oscillating magnetic field generates the so-called eddy currents, that heat up the silicon by Joule effect until melting. As a result, electrical energy is stored in the form of the latent heat. In the second case, concentrated solar power heats the inner walls of the vessel containing the silicon. If the sunlight concentration factor is high enough [5] (above 1000 suns) the solar heat will produce the silicon melting and consequently, solar energy will be stored as latent heat. Other arrangements not illustrated in this paper may use the waste heat from high temperature industrial processes or other means of electric heating.

In both cases of Fig.1 the stored heat is released in the form of electricity by using a TPV generator, which comprises a number of infrared sensitive photovoltaic cells that directly produce electricity from radiant heat. When electricity is demanded from the TES system, the TPV generator is moved in the cylindrical cavity formed by the inner walls of the vessel, from now-on referred to

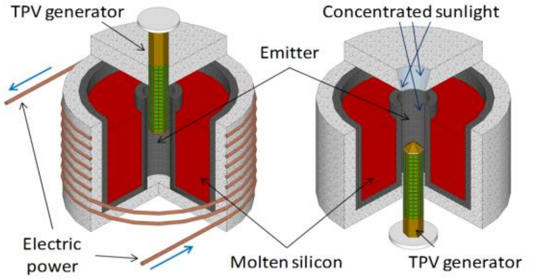

Fig. 2. Electric-TES (left) and solar-TES (right) systems utilizing molten silicon and TPV cells for electricity production [4].

as emitter (Fig.1). Then, the TPV converter is irradiated by the emitter (which is in direct contact with the molten silicon) and produces electricity. During this process, the silicon progressively solidifies creating a crust of solid around the emitter. This crust difficults the flow of heat from the liquid silicon to the emitter. However, the high solid-phase thermal conductivity of silicon enormously mitigates the impact of this effect on the output system power.

Notice that these systems have the possibility of delivering not only electricity, but also heat from the TPV cells cooling, which might be beneficial in some particular applications such as in domestic heating, where the output coolant temperatures of 40-70ºC match perfectly with the heating temperature requirements.

2.2 Silicon PCM

The energy density (stored energy per unit of volume or weight) of this system relies on the latent heat of the PCM. Besides, the PCM melting temperature determines the achievable TPV conversion efficiency and power density (W/cm^2). Thus, high melting point and high latent heat are general desirable properties for the PCM. Among all the possible candidates, silicon stands out as the most promising material [6], due to its high latent heat of 1800 J/g, melting temperature of 1410ºC (see Fig.3), very low cost of $1.7/kg, and the great abundance on earth. Besides, its high thermal conductivity (above 25 W/m-K for solid phase at high temperatures [7]) facilitates the heat extraction without using complex encapsulates, as needed in the case of molten salts.

2.2 TPV cells

Low bandgap III-V semiconductors, such as GaSb, InGaAs or InGaAsSb are typical materials for developing high efficient TPV cells. These compounds provide the best performance at the expense of utilizing expensive and relatively scarce elements such as indium, arsenic or gallium. While the cost issue is drastically mitigated by the very high power density (watts per unit of device area) that is produced by TPV cells in the proximities of a ~1400ºC incandescent source (above 3 W/cm^2 [8]), the material scarcity issue can be further mitigated by several technological options [9] such as the growth of III-V compounds on silicon substrates (using graded buffer layers) or by wafer-bonding techniques. Another option consists of using directly crystalline silicon (c-Si) cells or Si/Ge compounds and quantum structures. The latter may consist of strain-balanced Si/Ge multi quantum wells (MQW) or Ge/Si quantum dots (QD) structures [10], both grown on silicon substrates. Although very few works have been reported on these particular structures, their potential of producing bandgaps as low as ~ 0.8eV on silicon substrates has great benefits for TPV energy conversion.

The TPV cells also incorporate spectral control elements for turning back to the heat source those sub-bandgap photons not absorbed by the cell (photon recycling). This is the key aspect that enables high TPV conversion efficiency. The typical spectral control elements in the TPV cell are: back surface reflector (BSR) and a front surface filter (FSF).

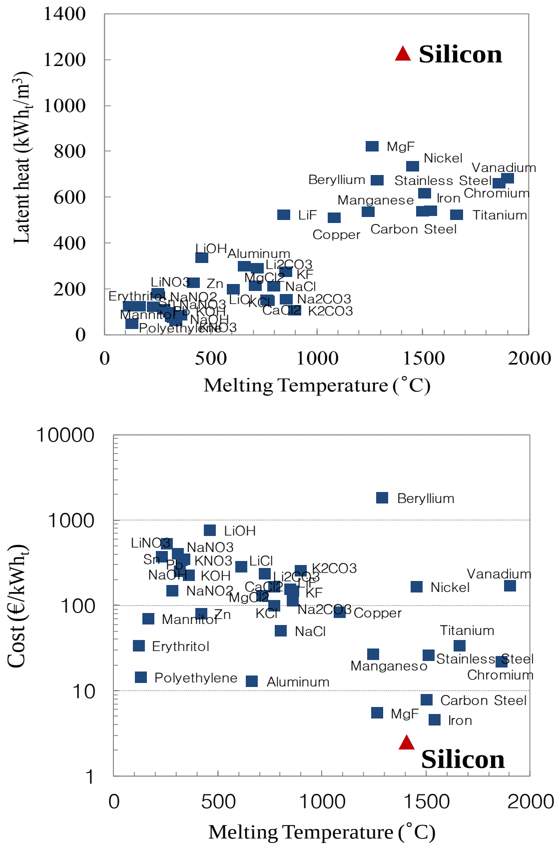

Fig. 3. The key attractiveness of silicon for TES: (top) Extremly high latent heat of fusion; (bottom) low cost per unit of energy stored as latent heat (from several sources). Metallurgic silicon is considered.

3 SYSTEM MODEL

3.1 Model assumptions

We have solved analytically the transient solidification problem taking place in the ES system during the power discharge by using a quasi-stationary 1D analytical model as in [11]. This model assumes a moving solid-liquid cylindrical interface at a distance r_m(t) from the emitter. The silicon's parameters are: latent heat of fusion (1800 J/g), thermal conductivity (25 W/m-K for solid and 50 W/m-k for liquid), density (2520 kg/m^3), heat capacity (1040 J/kg-K for both solid and liquid) and melting point of 1410ºC. The TPV cells are assumed to work at 50ºC and have an integrated back-surface reflector (BSR) that turns back to the emitter the sub-bandgap photons. Recombination in the TPV cells is modeled according to the detailed balance theory [12] and using the internal photoluminescence efficiency to include non radiative recombination mechanisms. Internal photoluminescence efficiency approaches 100% in the ideal case of purely

TABLE I
ENERGY STORAGE SYSTEM OUTPUT CHARACTERISTICS

TPV cell @50ºC	BSR reflect	Released Energy (kWh)		Energy density **(*)** (kWh/m^3)		Efff (%)	Output Electrical Power (kW)			Discharge time (**) (hours)
		Heat	Electricity	Total	Electricity		Peak	Avg	Minimum	
HQ InGaAs Eg=0.74eV η_{int}=95%	100%	399.4	501.8	796.9	443.5	55.7	72.6	32.0	23.2	15.6
	90%	602.8	301.0	799.1	266.1	33.3	71.0	22.5	16.0	13.4
	80%	711.6	201.2	807.1	177.9	22.0	69.9	17.5	11.6	11.5
LQ InGaAs Eg=0.74 eV η_{int}=20%	100%	503.0	390.1	789.7	344.9	43.7	58.7	23.6	18.3	16.5
	90%	660.3	243.7	799.4	215.5	27.0	58.6	18.2	13.0	13.4
	80%	747.1	165.7	807.1	146.5	18.1	58.6	14.4	9.5	11.5
c-Si Eg= 1.1 eV η_{int}=20%	100%	396.9	460.8	758.5	407.5	53.7	15.7	10.5	9.0	44.1
	90%	777.3	108.8	783.5	96.2	12.3	15.7	5.7	3.8	19.0
	80%	853.7	48.9	798.0	43.2	5.4	15.7	3.6	2.0	13.7

(*)Total system volume is $\pi L(R_2+0.1)^2$ = 1.1 m^3 (L=1m, R_1=0.2m and R_2=0.5m and the outer vessel walls of 10 cm thick).
(**) full-power discharge.

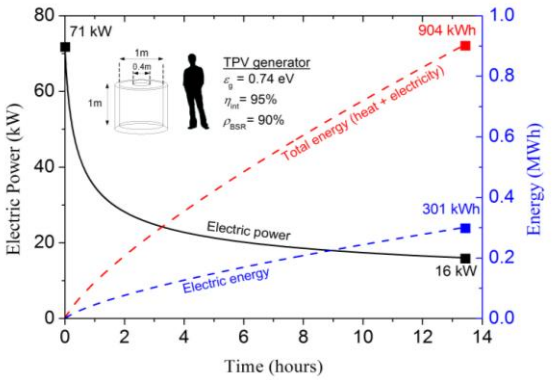

Fig. 4. Electric output power and energy as a function of time during the discharge of the ES system. HQ InGaAs TPV cells with η_{int}=95% and ρ_{BSR}=90% are assumed. The system syze is the same than in Table I (L=1m, R_1=0.2m and R_2=0.5m). Overall system heat-to-electricity conversion efficiency is 33.3% (see Table I). The electric energy density of the system is 266 kWh(electric)/m^3.

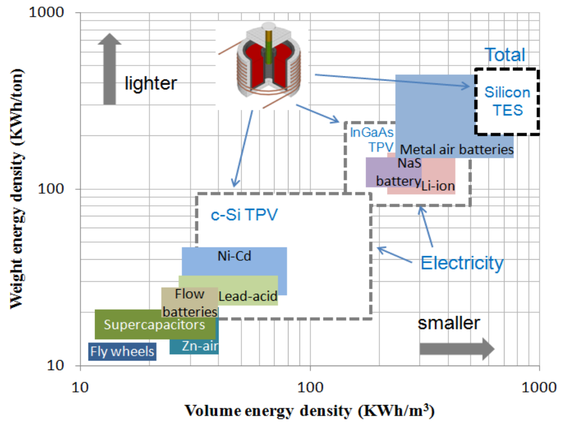

Fig. 5. Energy density of several electricity storage systems compared with that of the proposed ES system (from several sources). For the proposed system we differentiate between thermal energy density (labeled Silicon TES) and just electric energy density, which depends on the heat-to-electric energy conversion efficiency of the TPV cell.

radiative recombination. However, for high quality III-V semiconductors it is about 95% [13], and in the case of high quality crystalline silicon devices it is in the range of 10-20% (corresponding to external photoluminescence efficiency of 0.5-1% [14]).

3.2 Results and discussion

Table I shows the model results for the discharge of the TES system with L = 1 m, R_1 = 0.2 m and R_2 = 0.5 m (~ 1.1 m^3) and different TPV cells and sub-bandgap photon recycling efficiencies (BSR reflectivity). Initial condition is that emitter temperature equals the silicon's melting point, so that energy is released from the system during the silicon's solidification. The system is considered discharged when all silicon is solidified. Notice that the values in Table I refer to the full-power discharge mode, i.e. when the TPV converter is entirely introduced in the cavity from the beginning, which provides the highest power-to-discharge time ratio.

Notice that the particular geometry chosen in Table I determines the power-to-capacity ratio. Smaller TPV converters (smaller R_1) would lead to lower power (smaller TPV cell area) and higher storage capacity (higher volume of silicon). We chose this particular geometry to illustrate the system performance.

The system shows a high initial power peak (Fig.4), corresponding to the maximum emitter temperature of ~1410ºC (silicon melting point). The power diminishes very rapidly due to the early formation of a crust of solid silicon around the emitter, which difficults the flow of heat. However, the high thermal conductivity of silicon makes this effect tolerable. Notice that the discharge process can be slowed down by introducing just a part of the TPV generator in the cavity, so that the output power is reduced and the discharge time is increased.

From Table I we conclude that total energy densities (heat plus electricity) of ~ 800 kW/m^3 and electric energy densities of up to 450 kWh/m^3 are attainable, which is 2 to 5 times (if total energy is accounted) higher than that of Li-ion batteries (Fig.5). The best electric performance is obtained for low bandgap cells (e.g. InGaAs), for which an TES system of ~1 m^3 provides enough energy (heat plus electricity) to power about 30 Spanish homes during 24 hours. Notice that the average consumption of a Spanish home is 10,500 kWh/home-year (28.8 KWh/home-day), from which electricity represents the 36%. By utilizing cost-effective c-Si cells with 90% sub-bandgap photon-recycling efficiency, the proposed TES system could deliver, in one cycle, as much electricity (~90 kWh/m^3) as lead-acid batteries of the same size, and provides an extra ~780 kWh of thermal energy (e.g. hot water at ~50ºC).

4 SUMMARY AND CONCLUSIONS

A novel conceptual system design for thermal energy storage utilizing molten silicon and thermophotovoltaic cells has been presented. The benefit of this system relies on the high energy density, low cost potential and availability of constituent materials. Thermal energy densities approaching 1 MWh/m^3 are achievable due to the extremely high latent heat of silicon. Part of this energy is converted to electricity upon demand by the TPV cells, while other part is delivered directly as heat. If only electricity output is considered, the attainable electric energy density is in the range of 150-400 Kwh/m^3 (comparable to Lithium-ion batteries) for TPV cells made of low bandgap (0.74eV) III-V semiconductors such as InGaAs or GaSb. Values in the range of 40-100 kWh/m^3 (comparable to lead-acid batteries) are possible by using less expensive crystalline silicon TPV cells. These systems could be applied to both solar and electric energy storage, as well as an alternative solution to waste heat recovery in high temperature industries.

5 ACKNOWLEDGEMENTS

Authors acknowledge the financial support of the Comunidad de Madrid through the Programme MADRID-PV (Grant number S2013/MAE-2780) and from the Spanish Ministerio de Economía y Competititvidad through the Project PROMESA (grant N. ENE2012-37804-C02-01).

6 REFERENCES

[1] Interantional Energy Agency, “Technology Roadmap: Energy Storage,” Mar. 2014.

[2] “marketsandmarkets.com, 2013.” .

[3] D. Barlev, R. Vidu, and P. Stroeve, “Innovation in concentrated solar power,” *Sol. Enegy Mater. Sol. Cells*, vol. 95, pp. 2703–2725, 2011.

[4] A. Datas, A. Martí, C. del Cañizo, and A. Luque, “Electric energy storage system,” 14/198,14.

[5] A. Datas, D. L. Chubb, and A. Veeraragavan, “Steady state analysis of a storage integrated solar thermophotovoltaic (SISTPV) system,” *Sol. Energy*, vol. 96, pp. 33 – 45, 2013.

[6] D. L. Chubb, B. S. Good, and R. A. Lowe, “Solar thermophotovoltaic (STPV) system with thermal energy storage,” 1995, pp. 181–198.

[7] Y. B. Magomedov and G. G. Gadjiev, “High-temperature thermal conductivity of silicon in the solid and liquid states,” *High Temp.*, vol. 46, no. 3, pp. 422–424, May 2008.

[8] A. Datas, “Optimum semiconductor bandgaps in single junction and multijunction thermophotovoltaic converters,” *Sol. Energy Mater. Sol. Cells*, vol. 134, no. 0, pp. 275 – 290, 2015.

[9] N. Jain and M. K. Hudait, “III–V Multijunction Solar Cell Integration with Silicon: Present Status, Challenges and Future Outlook,” *Energy Harvest. Syst.*, pp. 121–145, 2014.

[10] B. Bitnar, “Silicon, germanium and silicon/germanium photocells for thermophotovoltaics applications,” *Semicond. Sci. Technol.*, vol. 18, pp. S221–S227, 2003.

[11] A. Veeraragavan, L. Montgomery, and A. Datas, “Night time performance of a storage integrated solar thermophotovoltaic (SISTPV) system,” *Sol. Energy*, vol. 108, no. 0, pp. 377–389, Oct. 2014.

[12] A. Datas and C. Algora, “Detailed balance analysis of solar thermophotovoltaic systems made up of single junction photovoltaic cells and broadband thermal emitters,” *Sol. Energy Mater. Sol. Cells*, vol. 94, no. 12, pp. 2137–2147, 2010.

[13] M. A. Steiner, J. F. Geisz, I. Garcia, D. J. Friedman, A. Duda, W. J. Olavarria, M. Young, D. Kuciauskas, and S. R. Kurtz, “Effects of Internal Luminescence and Internal Optics on and of III–V Solar Cells,” *IEEE J. Photovolt.*, vol. 3, no. 4, pp. 1437–1442, Oct. 2013.

[14] M. A. Green, J. Zhao, A. Wang, P. J. Reece, and M. Gal, “Efficient silicon light-emitting diodes,” *Nature*, vol. 412, no. 6849, pp. 805–808, Aug. 2001.